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Multiplexing

- Multiplexing
  - a process where multiple analog message signals or digital data streams are combined into one signal over a shared medium
- Types
  - Time division multiplexing
  - Frequency division multiplexing
- Optically
  - Time division multiplexing
  - Wavelength division multiplexing

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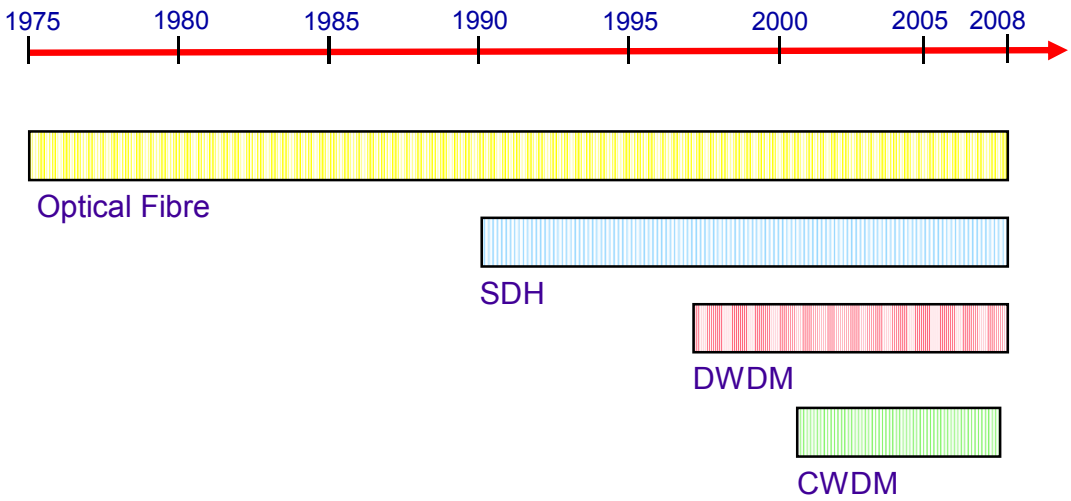
Timeline



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Problems and Solutions

Problem:

Demand for massive increases in capacity

↓

Immediate Solution:

Dense Wavelength Division Multiplexing

↓

Longer term Solution:

Optical Fibre Networks

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Wavelength Division Multiplexing

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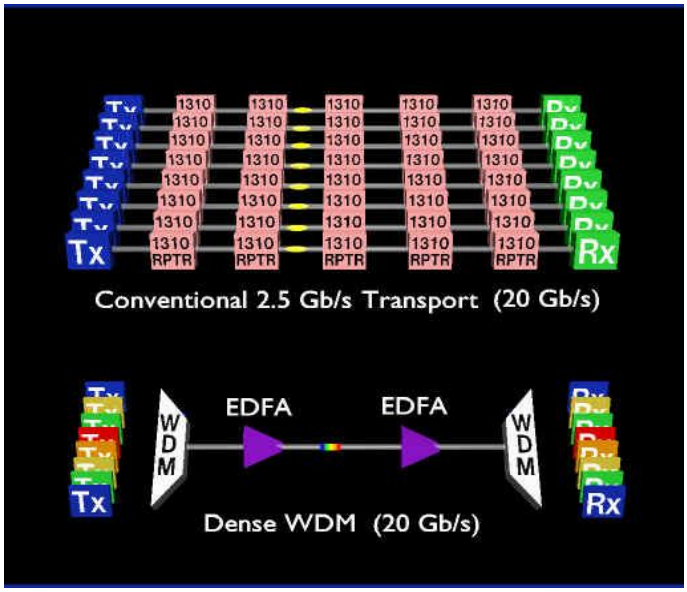
Dense WDM



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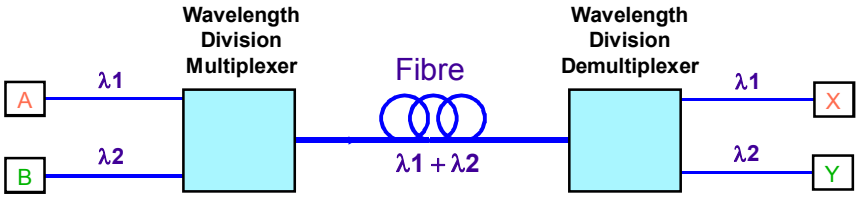
WDM Overview



- Multiple channels of information carried over the same fibre, each using an individual wavelength
- A communicates with X and B with Y as if a dedicated fibre is used for each signal
- Typically one channel utilises 1320 nm and the other 1550 nm
- Broad channel spacing, several hundred nm
- Recently WDM has become known as Coarse WDM or CWDM to distinguish it from DWDM

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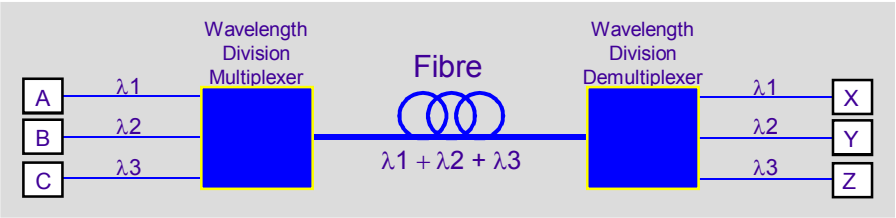
WDM Overview



- Multiple channels of information carried over the same fibre, each using an individual wavelength
- Attractive multiplexing technique
  - High aggregate bit rate without high speed electronics or modulation
  - Low dispersion penalty for aggregate bit rate
  - Very useful for upgrades to installed fibres
  - Realisable using commercial components, unlike OTDM
- Loss, crosstalk and non-linear effects are potential problems

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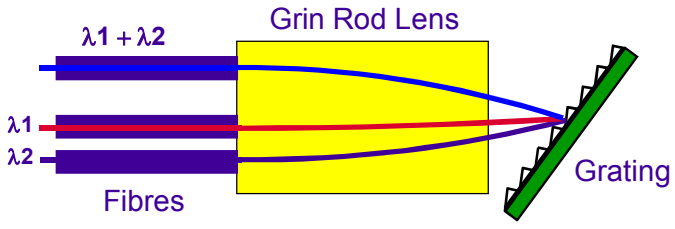
WDM Multiplexers/Demultiplexers

- Wavelength multiplexer types include:
  - Fibre couplers
  - Grating multiplexers
- Wavelength demultiplexer types include:
  - Single mode fused taper couplers
  - Grating demultiplexers
  - Tunable filters



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Tunable Sources

- WDM systems require sources at different wavelengths
- Irish researchers at U.C.D. under the ACTS program are developing precision tunable laser sources
- Objective is to develop a complete module incorporating:
  - Multisection segmented grating Distributed Bragg Reflector Laser diode
  - Thermal and current drivers
  - Control microprocessor
  - Interface to allow remote optical power and wavelength setting

ACTS BLISS
AC069 Project

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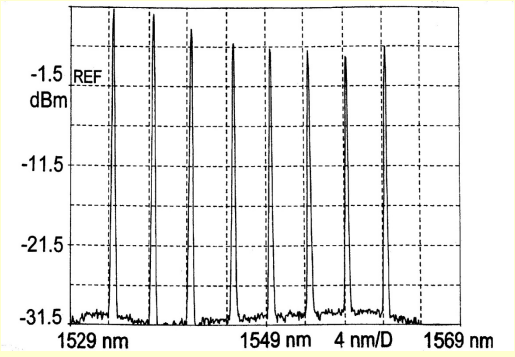
Early DWDM: CNET 160 Gbits/sec WDM

- 160 Gbits/s
- 8 channels, 20 Gbits/s each
- Grating multiplex/demultiplex
- 4 nm channel spacing
- 1533 to 1561 nm band
- 238 km span
- 3 optical amplifiers used



Multiplexer Optical Output Spectrum

Art O'Hare, CNET, PTL May 1996

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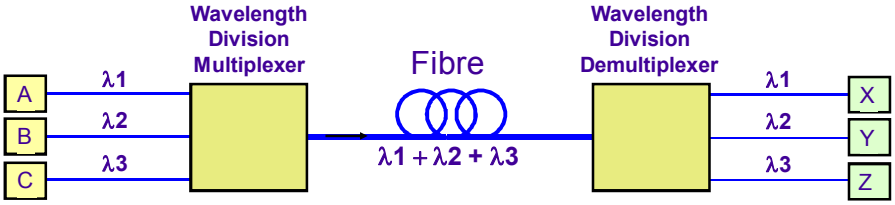
Dense Wavelength Division Multiplexing



- Multiple channels of information carried over the same fibre, each using an individual wavelength
- *Dense WDM* is WDM utilising closely spaced channels
- Channel spacing reduced to 1.6 nm and less
- Cost effective way of increasing capacity without replacing fibre
- Commercial systems available with capacities of 32 channels and upwards; > 80 Gb/s per fibre

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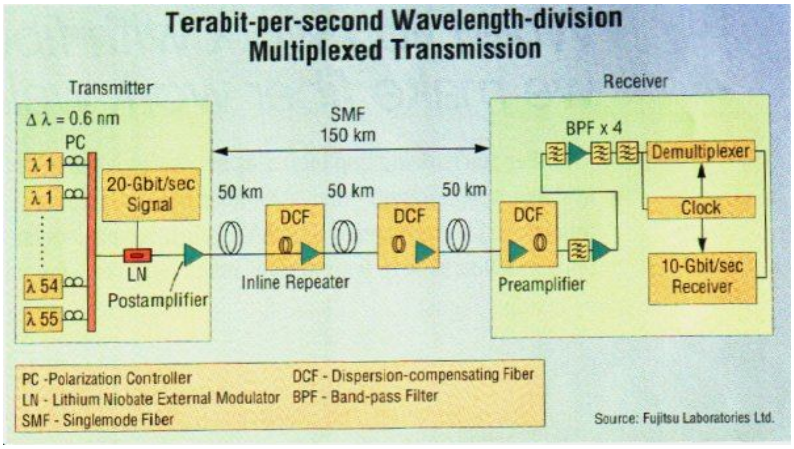
Terabit Transmission using DWDM

- 1.1 Tbits/sec total bit rate (more than 13 million telephone channels)
- 55 wavelengths at 20 Gbits/sec each
- 1550 nm operation over 150 km with dispersion compensation
- Bandwidth from 1531.7 nm to 1564.07 nm (0.6 nm spacing)



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Expansion Options

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Capacity Expansion Options (I)

- Install more fibre
  - New fibre is expensive to install (Euro 100k + per km)
  - Fibre routes require a right-of-way
  - Additional regenerators and/or amplifiers may be required
- Install more SDH network elements over dark fibre
  - Additional regenerators and/or amplifiers may be required
  - More space needed in buildings

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Capacity Expansion Options (II)

- Install higher speed SDH network elements
  - Speeds above STM-16 not yet trivial to deploy
  - STM-64 price points have not yet fallen sufficiently
  - No visible expansion options beyond 10 Gbit/s
  - May require network redesign
- Install DWDM
  - Incremental capacity expansion to 80 Gbits/s and beyond
  - Allows reuse of the installed equipment base

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DWDM Advantages and Disadvantages

DWDM Advantages

- Greater fibre capacity
- Easier network expansion
  - No new fibre needed
  - Just add a new wavelength
  - Incremental cost for a new channel is low
  - No need to replace many components such as optical amplifiers
- DWDM systems capable of longer span lengths
  - TDM approach using STM-64 is more costly and more susceptible to chromatic and polarization mode dispersion
- Can move to STM-64 when economics improve

DWDM Disadvantages

- Not cost-effective for low channel numbers
  - Fixed cost of mux/demux, transponder, other system components
- Introduces another element, the frequency domain, to network design and management
- SONET/SDH network management systems not well equipped to handle DWDM topologies
- DWDM performance monitoring and protection methodologies developing

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DWDM Standards

- ITU Recommendation is G.692 "Optical interfaces for multichannel systems with optical amplifiers"
- G.692 includes a number of DWDM channel plans
- Channel separation set at:
  - 50, 100 and 200 GHz
  - equivalent to approximate wavelength spacings of 0.4, 0.8 and 1.6 nm
- Channels lie in the range 1530.3 nm to 1567.1 nm (so-called C-Band)
- Newer "L-Band" exists from about 1570 nm to 1620 nm
- Supervisory channel also specified at 1510 nm to handle alarms and monitoring

International Telecommunication Union

Source: Master 7_4

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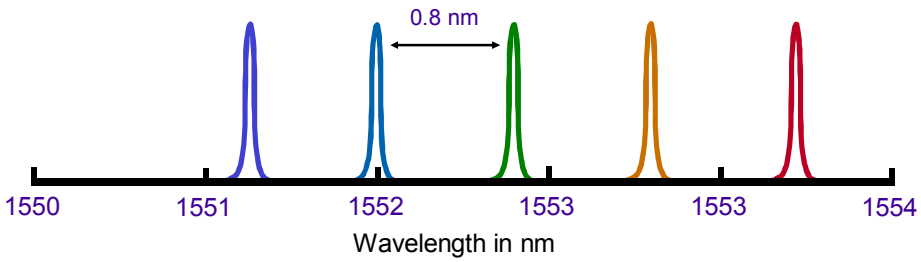
Channel Spacing

- Trend is toward smaller channel spacings, to incease the channel count
- ITU channel spacings are 0.4 nm, 0.8 nm and 1.6 nm (50, 100 and 200 GHz)
- Proposed spacings of 0.2 nm (25 GHz) and even 0.1 nm (12.5 GHz)
- Requires laser sources with excellent long term wavelength stability, better than 10 pm
- One target is to allow more channels in the C-band without other upgrades



ITU DWDM Channel Plan
0.4 nm Spacing (50 GHz)

So called
ITU *C-Band*

81 channels defined

Another band called
the *L-band* exists
above 1565 nm

All Wavelengths in nm

1528.77	1534.64	1540.56	1546.52	1552.52	1558.58
1529.16	1535.04	1540.95	1546.92	1552.93	1558.98
1529.55	1535.43	1541.35	1547.32	1553.33	1559.39
1529.94	1535.82	1541.75	1547.72	1553.73	1559.79
1530.33	1536.22	1542.14	1548.11	1554.13	1560.20
1530.72	1536.61	1542.54	1548.51	1554.54	1560.61
1531.12	1537.00	1542.94	1548.91	1554.94	
1531.51	1537.40	1543.33	1549.32	1555.34	
1531.90	1537.79	1543.73	1549.72	1555.75	
1532.29	1538.19	1544.13	1550.12	1556.15	
1532.68	1538.58	1544.53	1550.52	1556.55	
1533.07	1538.98	1544.92	1550.92	1556.96	
1533.47	1539.37	1545.32	1551.32	1557.36	
1533.86	1539.77	1545.72	1551.72	1557.77	
1534.25	1540.16	1546.12	1552.12	1558.17	

Speed of Light assumed to be 2.99792458×10^8 m/s

ITU DWDM Channel Plan
0.8 nm Spacing (100 GHz)

All Wavelengths in nm

1528.77	1534.64	1540.56	1546.52	1552.52	1558.98
1529.55	1535.43	1541.35	1547.32	1553.33	1559.79
1530.33	1536.22	1542.14	1548.11	1554.13	1560.61
1531.12	1537.00	1542.94	1548.91	1554.94	
1531.90	1537.79	1543.73	1549.72	1555.75	
1532.68	1538.58	1544.53	1550.52	1556.55	
1533.47	1539.37	1545.32	1551.32	1557.36	
1534.25	1540.16	1546.12	1552.12	1558.17	

Speed of Light assumed to be 2.99792458×10^8 m/s

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Mux/Demuxes

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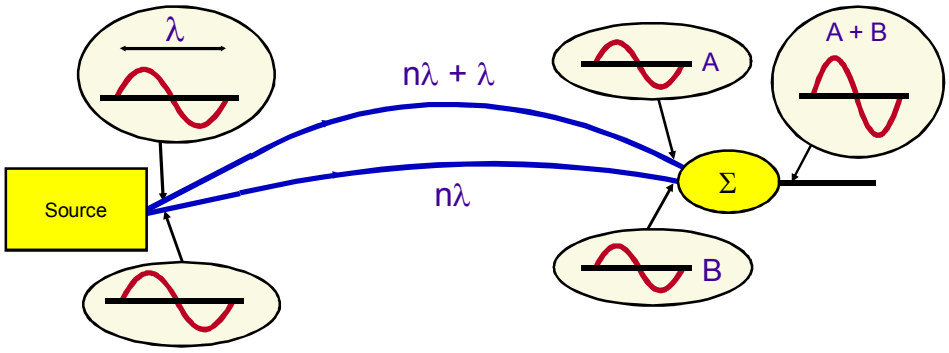
Constructive Interference



- Travelling on two different paths, both waves recombine (at the summer, Σ)
- Because of the λ path length difference the waves are in-phase
- Complete reinforcement occurs, so-called constructive interference

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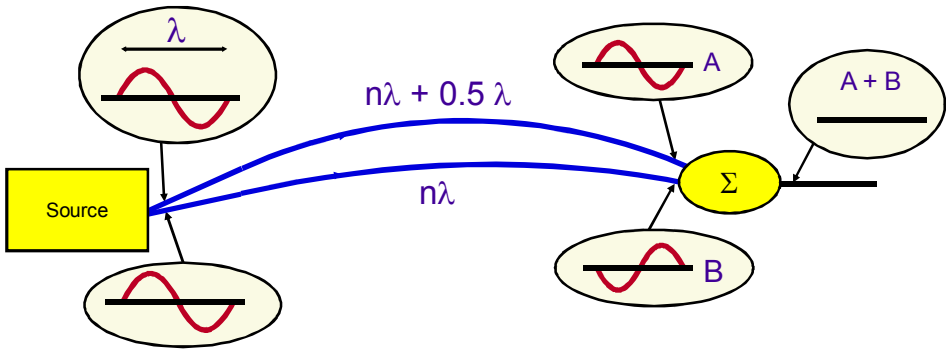
Destructive Interference



- Travelling on two different paths, both waves recombine (at the summer, Σ)
- Because of the 0.5λ path length difference the waves are out of phase
- Complete cancellation occurs, so-called destructive interference

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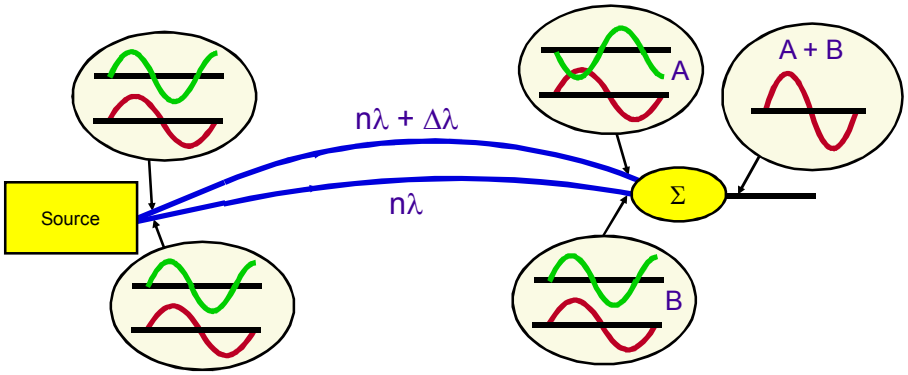
Using Interference to Select a Wavelength



- Two different wavelengths, both travelling on two different paths
- Because of the path length difference the "Red" wavelength undergoes constructive interference while the "Green" suffers destructive interference
- Only the Red wavelength is selected, Green is rejected